Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 41 (2016) 875 – 880

www.elsevier.com/locate/procedia

48th CIRP Conference on MANUFACTURING SYSTEMS - CIRP CMS 2015

Process concepts for gear finish hobbing

Fritz Klocke[a], Christoph Löpenhaus[a], Deniz Sari[a,*]

[a]*Laboratory for Machine Tools and Production Engineering, Steinbachstraße 19, 52074 Aachen, Germany*

* Corresponding author. Tel.: +49-241-80-28285; fax: +49-241-80-22293. *E-mail address*: d.sari@wzl.rwth-aachen.de

Abstract

In the process chain for gear manufacturing, gear hobbing is one of the most productive processes for soft machining of gears. To reach a high quality after the soft machining, for example in gear finish hobbing, the requirements on the hobbing process increases significantly. To get a high quality part after soft machining, the process of gear hobbing is mostly divided in a roughing and a finishing cut. In the roughing process, the most amount of the material needs to get machined. The finishing process is used to get a high quality shape of the gear and to get low surface roughness. To get low cutting forces in the finishing step, the material stock after the roughing process has to be minimized. A low amount of stock on the flank offers the possibility to use high cutting speeds.

This paper deals with the investigation of the two cut processes in the gear hobbing. Especially, the tool life of different tool concepts are taken into account. The process design offers the opportunity to use the same tool for the roughing and the finishing cut or the choice of different tools. Using different tools, a special tool design for the finishing step would be possible. A comparison between these two concepts is the focus of the investigation.

Peer-review under responsibility of the scientific committee of 48th CIRP Conference on MANUFACTURING SYSTEMS - CIRP CMS 2015

Keywords: Machining; Gear; Hobbing; Carbide; Cutting; Productivity

Nomenclature

α_n	normal pressure angle of the workpiece (0) and tool (2)
β_2	helix angle of the workpiece
d_{a0}	outside diameter of the tool
δ_x	generated cut deviation
δ_y	feed mark deviation
f_a	axial feed
h	radial feed
v_c	cutting speed
m_n	normal module
n_i	number of gabs of the tool
z_0	number of starts of the tool
z_2	number of teeth of the workpiece
pr_{p0}	protuberance
t_H	main process time
LF	leading flank
TF	trailing flank
L	tool life
WST	workpiece
VB	wear width

1. Motivation

In many process chains for gear manufacturing fine machining is the final machining process. Therefore, mostly fine machining is the quality defining step in gear manufacturing. Fine machining of gears occurs in hard or soft workpiece condition. For hard finishing, gear grinding and gear honing are the most common processes. Instead of hard finishing processes soft finishing processes offer an alternative in fine machining. The most common soft finishing processes are gear shaving and gear finish hobbing. Compared to gear shaving, gear finish hobbing offers high potentials to realize an economical and ecological finishing process of gears. By us-

Peer-review under responsibility of the scientific committee of 48th CIRP Conference on MANUFACTURING SYSTEMS - CIRP CMS 2015
doi:10.1016/j.procir.2015.12.099

ing a dry cutting process in finish hobbing, a completely dry process chain can be realized.

If the process of gear finish hobbing and the associated component characteristics are manageable, a shortened process chain can be realized. First, the functional surfaces and the outside shape have to be manufactured. During the subsequent hobbing process, shape deviations are kept to a minimum. Furthermore, the surface after hobbing has to meet strict requirements, because the tooth does not undergo further processing, in which deviations could be reduced. After heat treatment the part is ready for installation in a gearbox.

The process of gear finish hobbing is usually divided into a roughing and a finishing cut. During rough machining the largest amount of material is machined. The dimensional accuracy and desired surface quality is set by the finishing cut. To keep the machining forces low in the finishing cut and thus ensure dimensional accuracy, the stock left by the roughing cut should be low. A low stock leads to the possibility to use high cutting speeds while finishing.

To implement this processing technology, different tool concepts could be used. The superiority of a special combination hob for finish hobbing against a conventionally designed hob is not scientifically proven today. Therefore, an evaluation of these tool concepts depending on the selected machining strategy will be carried out in this paper.

2. State of the art

The gear finish hobbing has great economic potential, because an expensive hard finishing can be eliminated. A crucial requirement for the process gear finish hobbing is to keep occurring form deviations as small as possible. Hobbing always based on process-related form deviations. These are feed-mark-deviations δ_x and generating-cut-deviations δ_y [6].

Feed marks are formed in the axial direction of the workpiece due to the axial feed movement of the tool. The axial feed f_a corresponds to the distance moved by the hob during one rotation of the workpiece in the axial direction. These deviations occur in the tooth flank direction and can be calculated by formula (1) [16]:

$$\delta_x = \left(\frac{f_a}{\cos\beta}\right)^2 \cdot \frac{\sin\alpha_n}{4 \cdot d_{a0}} \tag{1}$$

Generating-cut-deviations resulting from the characteristic, shaping the tooth surface with a straight flank tool, interrupted by cuts. The involute is thus approximated by individual line segments. The amount of generating-cut-deviations can be determined by formula (2) [16]:

$$\delta_y = \frac{\pi^2 \cdot m_n \cdot z_0{}^2 \cdot \sin\alpha_n}{4 \cdot n_i{}^2 \cdot z_2} \tag{2}$$

In practice standard deviations for δ_x and δ_y often set to about 1 µm and smaller. Under the requirement to keep the characteristic deviations low and to produce high surface quality, the gear finish hobbing offers the possibility to realize a shortened process chain. Furthermore, shape deviations occurring during heat treatment are to be compensated in the gear finish hobbing process [1, 2]. The compensation of hardening distortions is an other requirement for the gear finish hobbing. After heat treatment other hard finishing operations of the gear will not occur.

Results of the research project IGF-17007 [3] showed, that the performance for finishing, the cutting material PM-HSS is significantly behind that of cemented carbide. Cemented carbide reaches the defined tool life criteria at a cutting speed of v_c = 1,400 m/min. PM-HSS reached this criteria at v_c = 500 m/min. Further improvements of the cutting material cemented carbide could be achieved through a cutting edge preparation. The tool life could be increased 30% by the cutting edge preparation method *Flakkoting*. [3]

3. Research objective and approach

The requirements, brought together in Fig. 1, result in the need to optimize the hobbing in roughing and finishing cut. The objective of this article is "Evaluation of different tool concepts for hobbing in a roughing and a finishing cut". Besides the scientific motivation, the economics of this objective can be derived, because the resulting tool costs and productivity can be positively influenced by a statement to the appropriate tool concept.

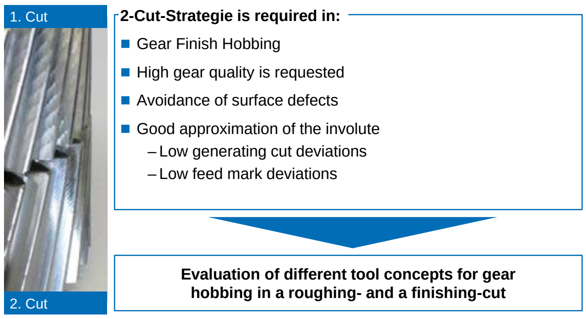

Fig. 1. Objective of the investigation

To achieve the objective, machining trials have to be conducted, which map the performance of the tool systems. There, the tool wear is detected in order to allow statements about the tool life during the hobbing process depending on the tool system. Moreover, the tool systems is evaluated by comparison of the theoretical process main time, in terms of productivity. To ensure comparability, the same parameter sets with conventional hobs and with special combination hobs are displayed. A detailed description of the gear data and the test parameters are given in Chapter 4.

4. Investigation of the 2-cut process

For the gear finish hobbing, consisting of pre- and finish machining, different tool systems can be used, see Fig. 2.

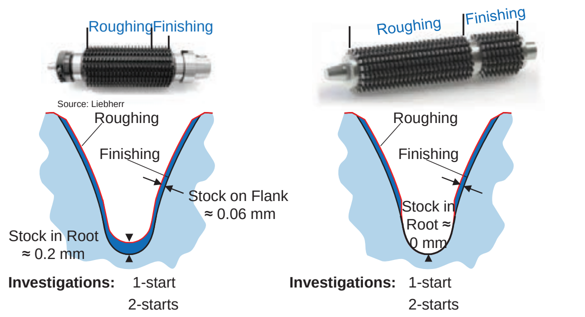

Fig. 2. Tool concepts for 2-cut-strategy-hobbing

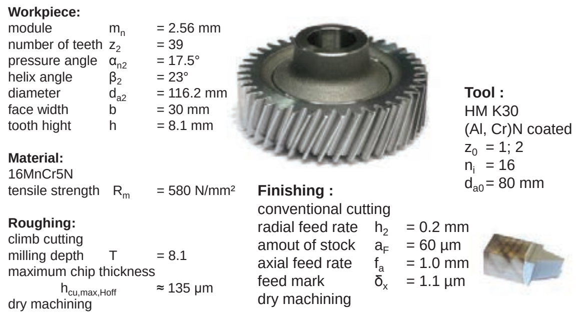

Fig. 3. Gear data for investigation

Thus, it is possible to use a conventional hob with a consistently uniform profile, Fig. 2 left. With this roughing and finishing cuts can be performed on different or on the same hob area. Characteristic of this tool concept is the tooth root machining for roughing and the finishing. In the machining test underlying this report, a stock of q = 60 µm is adjusted, which resulted a tooth root stock of 200 µm. The distribution of cutting edge load of roughing and finishing is provided by the use of a combination tool on, see Fig. 2 on the right. Here, the possibility is to use an other profile for finishing than for roughing. To reduce the tool load in the finishing cut, the profile of the roughing area can be executed with a protuberance and the profile of the finishing area with a lower tooth height, whereby no tooth root machining takes place during finishing. Thus, there is no chip forming at the tool tip, only the stock on the flanks is machined, which is also q = 60 µm. As a result, an increased loading capacity of the cutting edge is avoided at high cutting speeds during finishing cut and the tool life can be increased [7]. The optimization of the mentioned concept of combination tool was discussed extensively in [3, 4, 5, 10]. Also a combination tool was used for gear finish hobbing during the AiF research project IGF-17262 N for the production of test gears at WZL [2].

Using a combination tool for gear finish hobbing, the first and the second cut take place on two different tool areas. While the use of the combination tool performs the roughing and finishing cuts on two separate tool areas, the use of conventional hobs offers the possibility to machine on derived or on the same area. The focus of the presented studies is on the theoretical separation of the two areas.

To investigate the performance of different tool concepts for gear finish hobbing, the gear geometry and process parameters shown in Fig. 3 were used. This gear geometry was used in different investigations for the gear finish hobbing before [3, 4].

The workpiece has a module of m_n = 2.56 mm and z_2 = 39 teeth. The helix angle is set to β_2 = 23° and the pressure angle to α_n = 17.5°. The workpiece material for all investigations is case hardened steel 16MnCr5 with a tensile strength of R_m = 580 N/mm^2. All cutting trials were performed using tools made out of cemented carbide K30 coated with (Al, Cr) N in the fly cutter process.

The fly cutter process was confirmed as an analogy trial for hobbing in a variety of researches [4, 8, 11, 12, 13]. For roughing and finishing 1-start and 2-start tools were used. All studies presented were operated in dry machining. For machining in the roughing process the cutting speed was set to v_c = 360 m/min. The axial feed of the 1-start tool is $f_{a,1gg}$ = 3.65 mm and $f_{a,2gg}$ = 1.1 mm for the 2-start tool. Here, the maximum chip thickness by *Hoffmeister* [9, 14] in both cases was set to $h_{cu,max,Hoff}$ = 135 µm. Therefor a comparison of the roughing analyzes is guaranteed.

For the finishing cut the cutting speed was v_c = 1,000 m/min at conventional cutting direction. The parameters are orientated to the results of the previous studies from the research project IGF 17007 N [3]. The axial feed of the finishing cut is for both tool designs, 1-start and 2-starts, set to f_a = 1 mm. This leads according to [16] to feed-mark-deviations of δ_x = 1.1 µm. Since the height of the deviations from the ideal tooth flank for gear finish hobbing are constructive intended, the finishing cut was designed according to this size.

4.1. Finishing process

Using a penetration calculation for gear hobbing, the occurring maximum chip thicknesses could calculated before [9]. The maximum chip thickness of the conventional hob for the 1-start version is at $h_{cu,max}$ = 27 µm and for the 2-start version at $h_{cu2,max}$ = 48 µm. This is always achieved on the tool tip. In the area of tool flanks the reached chip thicknesses are lower. Using the combination tool the maximum chip thickness is located on the flanks. For 1-start tools the maximum chip thickness is $h_{cu,max}$ = 12 µm and for the 2-start version at $h_{cu,max}$ = 18 µm. Furthermore, it is evident using the combination tool no chip forming at the tip of the tool takes place.

In the following, the wear behavior of the tools in the different embodiments is evaluated. Therefore, the development of the flank wear of two versions are presented in Fig. 4 and Fig. 5. On the abscissae the tool life in meters is plotted, on the ordinate the wear width in micro meters. Fig. 4 shows the results of the trial with the use of a 2-start tool with machining of the tooth root, using a conventional hob.

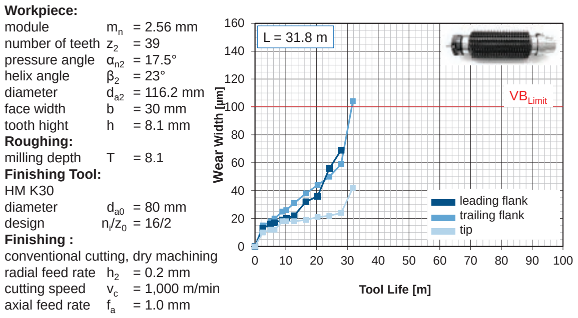

Fig. 4. Wear behaviour in finishing of a conventional hob

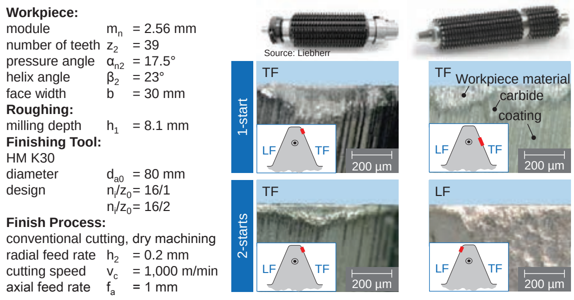

Fig. 6. Specific of wear after finishing

For this purpose, the wear patterns of the leading and the trailing flank as well as the tip are presented and correspondingly color coded. The tool life criterion is at a maximum wear width of VB = 100 µm. This is also marked in the diagram.

The wear widths of leading and trailing flank are comparable. These increase progressively to a value of L = 31.8 m until the wear width reached the tool life criterion on the trailing flank. The width of flank wear on the tool tip has reached VB = 41 µm at this time.

For comparison the development of the wear widths in the finishing cut, when using a 2-start combination tool, is shown in the following diagram, see Fig. 5. Here, the flank wear of the leading and trailing flank is mapped. In the area of the tip cutting edge no chip forming occurs, so this area is not considered. The wear widths on both flanks increases almost linearly, so that for a tool life of L = 99.1 m the tool life criteria is exceeded on the leading flank.

As mentioned above, while using a combination tool the option of not machining the tooth root and reduce the cutting load is exploited. However, the development of the flank wear at the tip is not life-determining when using a conventional hob, but the wear development on the flank cutting edge.

For accurate analysis of this difference, the characteristics of each lifetime-determining flank wear is shown in Fig. 6. The figures are assigned to the respective tool concepts as well as the 1-start and 2-start design. The depicted flank wear of the trials with the conventional hob and machining the tooth root, reaches its maximum on the trailing flank near the tip. Especially, in this area of the tool the load is higher due to the multi flank chip formation, see [15].

It should be noted, that the maximum wear of the conventional hob occurs in the evaluating area of the flanks. The comparison of the flank wear of the combination tool shows a different characteristic. The maximum of the flank wear of the 1-start version is centered on the trailing flank. Here, there is no influence from a multi flank chip formation. Another observation is the adhering work piece material at the worn cutting edge. For the 2-start tool this is not observed. Again, the maximum expression of the flank wear has occurred in the region near the corner radius, but now on the leading flank. In this case, there is no tooth root machining and no multi flank chip formation. However, the tool fails in the head corner radius. The wear develops here, as previously presented in the wear diagrams, slower than using the conventional hob.

Fig. 7 shows the achieved tool life for the investigations of the finishing cut. Conventional tools and combination tools with 1-start and 2-start were taken into account. On the ordinate the achieved tool life in meter is shown.

The results of the conventional hob are depicted in the left part and the combination hob in the right part. The 1-start and 2-start designs are displayed in different colors. The investigations of finishing with a conventional hob lead to a tool life of L = 45.8 m at 1-start and L = 31.8 m at the 2-start design. The use of a combination tool results in increasing the achieved tool life. So, these are L = 82.6 m at 1-start and L = 99.1 m at 2-start design. Summarized, the achieved tool life of a combination hob with a 2-start design is higher than the one of the 1-start design. Using a conventional hob, this reverses. This happens due to the shortfall of the minimum chip thickness with increasing relief face wear [3, 19].

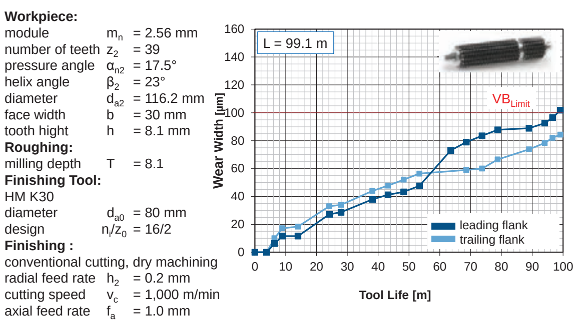

Fig. 5. Wear behaviour in finishing of a combination hob

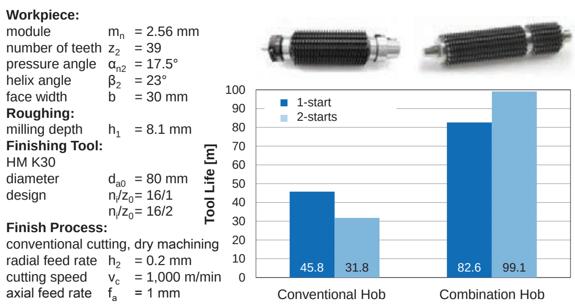

Fig. 7. Achieved tool life in finishing process

For the 1-start tool without tooth root machining the maximum chip thickness is at $h_{cu,max}$ = 12 µm and the medial chip thickness at $h_{cu,mit}$ = 3 µm. Because of the small chip thickness, the derivation of the minimal chip thickness is always a tool life determining factor.

4.2. Roughing Process

In the studies shown, the focus lies on the evaluation of the different versions of the finishing areas in gear finish hobbing. In order to develop a holistic evaluation of tool concepts, the performance of the tools in the roughing process must be analyzed as well. Therefore two attempts of roughing processes were executed. For this purpose, also the fly cutter process was used. A 1-start and a 2-start hobbing tool for the roughing process was investigated, too. All process parameters, except the axial feed, remained constant. For a 1-start hob this was set to $f_{a,1gg}$ = 3,65 mm and for the 2-start hob to $f_{a,2gg}$ = 1,1 mm. The profiles of the tools are designed as a standard shape and have no protuberances or further corrections. The profiles are identical to the finishing profile of conventional hobbing tools for finish machining. Since the roughing area of the combination tool for gear finish hobbing would be designed with a protuberance-profile, the results here are not exactly transferable. Here, the influence of protuberance-profile is not initially taken into account on the wear behavior. *Winkel* showed, that especially in the area of protuberance angle, tool life determining tool wear can occur for cemented carbide tools [8]. Therefore, the results presented for the conventional hobs are easily transferable and for the combination hob transferable within limits.

The development of the flank wear for investigations in the roughing cut are shown in Fig. 8. The division of the abscissa and the ordinate are chosen analogously to Fig. 4 and Fig. 5.

In the upper part of the figure, the development of the wear width of the leading and trailing flank and the tip cutting edge for the 1-start tool are depicted. In the lower part for the 2-start tool. The development of wear at the 1-start design hob shows a steadily rising flank wear of all three cutting edges. First, the initial wear development begins at VB = 20 µm for a tool life of approximately L = 1.5 m, which is considered as running-in wear with carbide tools [8, 17, 18]. flank. The wear width on the leading flank and on the tip cutting edge at this time was VB = 42 µm to 50 µm.

Assuming that, the wear amount linearly increases. The trailing flank achieved the tool life criterion at L = 28 m. The tool life criterion for the 2-start tool is achieved at L = 21.6 m, at the trailing

4.3. Evaluation of the tool concepts

In the next step, the results of the investigations of roughing and finishing are combined, to evaluate the tool systems afterwards. Therefore the six possible tooling concepts from the conducted investigations are divided (Fig. 9). These are the 1-start and 2-start conventional hobs. The tool length uniformly executed tool design, no different number of starts for roughing and finishing can be realized. Because of this, the corresponding fields are hidden. Since the combination tool allows greater design freedom, there are four possibilities consisting of a 1-start and 2-start roughing area as well as a 1-start and 2-start finishing area. For each tool concepts the obtained tool life in the different trials are joined. In this case the tool life is mentioned as the number of machined work pieces. These are divided into the tool life of roughing, $L_{WST,1}$, and the tool life of finishing step, $L_{WST,2}$.

To provide an assessment of the productivity of each concept, the achievable main process time t_H of hobbing in two cuts for each tool concept considered here are given. The concept of a 1-start designed conventional hob achieves a tool life for roughing of $L_{WST,1}$ = 22 and for finishing $L_{WST,2}$ = 36. The main process time using this tool concept for the given process parameters is at t_H = 53.4 seconds. The tool concept of the combination hob for example, with a 1-start exported roughing area and a 2-start exported finishing area reached the highest tool life. In workpieces this is $L_{WST,1}$ = 22 in finishing and $L_{WST,2}$ = 78 in roughing cut. This concept is in accordance highlighted. Furthermore, the resulting main process time in this case is t_H = 40,8 seconds.

The machining with 1-start roughing and a 2-start finishing area is not feasible with the use of conventional hob. Whereby the combination tool combines the advantages of this partition as well as the increased tool life in the finishing cut. This tool concept has the greatest potential here. Due to [3, 4, 5, 10], the potential of a combination tool allows a further increase for gear finish hobbing, building on the results presented in this report.

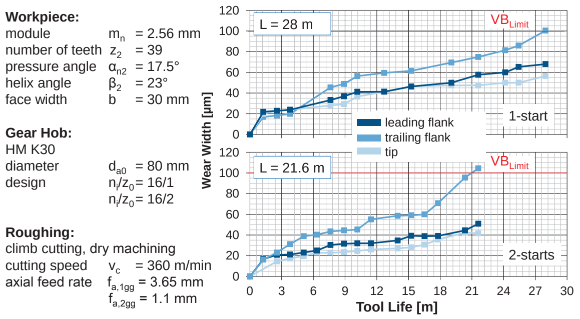

Fig. 8. Wear behaviour in roughing process

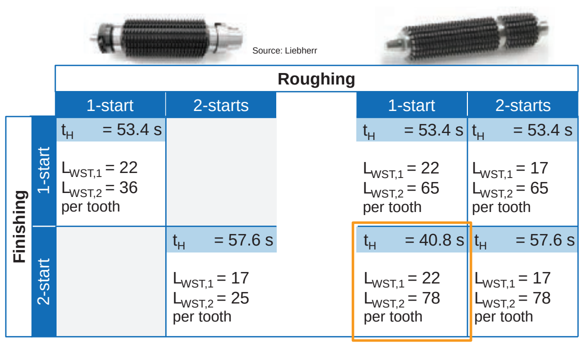

Fig. 9. Performance of investigated tool concepts

5. Summary

Gear finish hobbing offers the opportunity of soft finishing of gears. Compared to hard finishing, gear grinding or gear honing, soft finishing offers several key benefits. One benefit is to realize a more economical process. Besides gear finish hobbing, gear shaving is applied for soft finishing of gears. While cooling lubricants are required for gear shaving, gear finish hobbing allows dry machining. Consequently, by using gear finish hobbing a completely dry process chain can be realized. Therefore, compared to other finishing processes in gear manufacturing, ecological benefits result from gear finish hobbing.

The demand on gear finish hobbing is to manufacture gears with low shape deviations and high surface qualities. Therefore, the characteristic of gear finish hobbing is to machine the stock at high cutting speed. In this paper, the use of conventional hobs and combination hobs for a 2-cut process for manufacturing gears with low shape deviations were examined. The investigation has shown, that the use of a combination tool for finish hobbing reached a three times higher tool life in the finishing cut than the use of a conventional hob. Further investigations regarded the tool life of the roughing zone of the tools. By this, an overview of the performance of the tool concepts could be shown. Here, the maximum tool life reached a combination hob with a 1-start roughing area and a 2-start finishing area. Furthermore this concept provides the shortest machining time for the manufacturing step gear finish hobbing.

Finally, it can be summarized that the use of a combination hob with a 1-start roughing and a 2-start finishing area offers the highest performance. Using a conventional hob, this concepts is not feasible. Whereby the combination tool combines the advantages of this partition as well as the increased tool life in the finishing cut.

Acknowledgements

The authors gratefully acknowledge financial support by the WZL Gear Research Circle for the achievement of the project results.

References

[1] Schröder T: Analyse der Werkzeugbelastungen beim Zahnradschaben. Dissertation, RWTH Aachen, 2007

[2] Brecher C, Löpenhaus C, Sari D: Untersuchung des Einsatzverhaltens fertigwälzgefräster Stirnräder. Final report of AiF-Research-Project IGF-17262 N, 2015

[3] Klocke F, Löpenhaus C, Sari D: Potenziale des Fertigwälzfräsens von Verzahnungen. Final report of AiF-Research-Project IGF- 17007 N, 2015

[4] Schalaster R: Optimierung des Fertigwälzfräsens von Verzahnungen. Dissertation RWTH Aachen, 2012

[5] Klocke F, Schalaster R: Potenziale des Wälzfräsens im Schlichtschnitt bei extrem hohen Schnittgeschwindigkeiten. Final report of FWF-Research-Project No. 0178, 2009

[6] Bouzakis K.-D, Lili E, Michailidis N, Friderikos O: Manufacturing of Cylindrical Gears by Generating Cutting Processes: A Critical Synthesis of Analysis Methods. CIRP Annals - Manufacturing Technology 57 (2008) No. 2, pp. 676-696

[7] Winkel O: Fertigfräsen – heute und morgen. Leistungsfähigkeit und Potenziale der Weichfeinbearbeitung. In: Seminar „Feinbearbeitung von Zahnrädern", WZL , Aachen, 21.-22. November 2007

[8] Winkel O: Steigerung der Leistungsfähigkeit von Hartmetallwälzfräsern durch eine optimierte Werkzeuggestaltung. Dissertation, RWTH Aachen, 2005

[9] Brecher C, Brumm M, Krömer M: Design of Gear Hobbing Processes Using Simulations and Empirical Data. In: 9th CIRP Conference on Intelligent Computation in Manufacturing Engineering, Naples, 23.-24. June 2014

[10] Klocke F, Brumm M, Sari D: Gear Finish Hobbing – Potentials of Several Cutting Materials. In: Tagungsband zur „5th WZL Gear Conference in the USA 2014", Rochester NY, USA, 2014

[11] Kobialka C: Prozeßanalyse für das Trockenwälzfräsen mit Hartmetallwerkzeugen. Dissertation, RWTH Aachen, 2002

[12] Stuckenberg A: Vermeidung von Oberflächendefekten beim Wälzfräsen. Dissertation, RWTH Aachen, 2014

[13] Hipke M: Wälzfräsen mit pulvermetallurgisch hergestelltem Schnellarbeitsstahl. Dissertation, Otto-von-Guericke-Universität Magdeburg, 2011

[14] Hoffmeister B: Über den Verschleiß am Wälzfräser. Dissertation, RWTH Aachen, 1970

[15] Herzhoff S: Werkzeugverschleiß bei mehrflankiger Spanbildung. Dissertation, RWTH Aachen, 2013

[16] N. N.: Fette Verzahnungswerkzeuge. Product catalogue, 2008

[17] Maiuri TJ: The Gleason Works: Brief Synopsis of Carbide Wet and Dry Hobbing. Firmenschrift, Rochester NY, USA, 1998

[18] Tönshoff HK, Denkena B: In: Spanen. Grundlagen. 2. Auflage Springer-Verlag, Berlin, 2004

[19] Biermann D, Kahnis P: Analysis and simulation of size effects in micromilling. In: Production Engineering – WGP, Braunschweig, 2011